Module Wiring Example

John Wiles

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Selecting the proper cables and connecting them to a PV module seem like relatively simple tasks. However, as we have seen in the last three *Code Corner* columns, there are several steps involved. In this column and the next we will look at some typical PV systems. We'll examine how the module cables should be selected, sized, and connected to meet the requirements of the *National Electrical Code (NEC),* and to achieve a durable system that performs well.

Simple Example

Let's imagine that someone has given you a DC water pumping system consisting of a 24 volt submersible pump and two 75 watt, 12 volt PV modules. You have 90 foot (27 m) trees on your property, so you have to mount the two PV modules on the hill behind the house. The total distance from the PV array to the wellhead, and down the well to the pump, is 200 feet (61 m).

The PV modules have the following information printed on the back:

At STC:
Voc = 21.7 V, Isc = 5.8 A, Vmp = 17.3 V, I = 4.33 A

Maximum systems voltage = 600 V

Maximum series fuse = 15 A

#14-8 AWG conductors rated at 90°C required

Voc is the open-circuit voltage, Isc is the short-circuit current, mp refers to maximum power point, and STC refers to Standard Test Conditions of 25°C (77°F) and 1,000 W/m^2 irradiance.

Your area experiences 40°C (104°F) temperatures every summer. The modules are rack mounted, but frequently experience no cooling breezes. The normal winter low temperatures are about 0°C (32°F), and moderate winds are experienced in the winter. You choose to run direct burial conductors in the ground (24 inches (60 cm) deep), and choose USE-2 cable because a high-temperature, sunlight-resistant, wet-rated cable is required.

The required ampacity for the conductors is 9 amps (1.56 x 5.8 A = 9 A). The 1.56 safety factor is explained in *HP79's Code Corner,* on page 112. The high ambient temperatures in the summer cause the module junction boxes and areas adjacent to the modules to operate at about 65°C (149°F). With USE-2 conductors rated at 90°C (194°F), the temperature correction factor is 0.58.

At this point, you could select (guess) a cable size, correct its ampacity with this correction factor, and see if the corrected ampacity was greater than the required 9 A. Or you could calculate the 30°C (86°C) required ampacity by taking the 9 A and dividing by the temperature correction factor. In this case, the calculation yields 15.5 A (9 ÷ 0.58 = 15.5).

From *NEC* Table 310-16, we see that #14 (2 mm^2) USE-2 cable has a 30°C (86°F) ampacity of 25 amps, meeting the requirement. Since #14 is the smallest cable allowed for use with this module, it is our first choice. Incidentally, #14 USE-2 is not a commonly available cable type and size, and would have to be special ordered in large quantities (500 foot (152 m) minimum) from a major wire distributor. Section 240-3 of the code restricts #14 conductors to a 15 A overcurrent device, so we are permitted to use it.

Voltage drop can now be calculated. From Table 8 in Chapter 9 of the *NEC* (or *Code Corner, HP80),* we find that a #14 (2 mm^2) conductor has a resistance of 3.14 ohms per 1,000 feet (305 m). For our 400 foot (122 m) circuit length (round trip), the resistance will be 1.26 ohms (3.14 x 400 ÷ 1,000 = 1.26). At a maximum power current of 4.33 amps, the voltage drop in the circuit from the conductors alone is 5.5 volts, which is 23 percent of the nominal 24 volts in the system—way too much for a renewable energy system.

The module maximum power point current was selected as a compromise between the short-circuit current of the module and other unknown operating points that require less current than Isc. Pumps and PV modules operate all over the current range of the module, depending on temperature conditions, system design, time of day and other factors.

When we add a few milliohms (estimated at 0.005 ohms) for connections and a disconnect switch, we get even more drop. So we need to select a larger conductor size. Since #10 (5 mm^2) is more commonly available and is stocked by PV distributors, let's check it. The resistance for the 400 foot (122 m) run will be 0.496 ohms (1.24 x 4 ÷ 1,000 = 0.496), which yields a voltage drop of 2.14 volts or 8.9 percent. This is still too high.

Electrical supply houses and building supply stores normally stock #8 (8 mm^2) USE-2. The use of this conductor size would cut the voltage drop to 1.3 volts (0.778 x 400 ÷ 1,000 x 4.33 = 1.34), which is 5.6 percent of the nominal system voltage—still a little high.

The module terminals can accept a maximum conductor size of #8, so we must start getting creative. There are wire reducers made for just such applications. They are copper sleeves that fit over large cable sizes and reduce them to a smaller size that will fit into smaller terminals. We could also splice a larger conductor (used for the long run) to a #8 (8 mm^2) conductor that would fit the module terminals. The splicing devices would probably be split bolts, which need to be properly insulated with tape and installed in a protected (junction box) environment. There is usually not sufficient room in the module junction boxes to do these splices.

While we could continue to guess at larger conductor sizes, let's instead work the problem backwards. Assume that we want a voltage drop of no more than 2 percent, including wire drop and connection drop. We can solve for the necessary wire resistance per 1,000 feet as follows.

Maximum allowable voltage drop is 0.48 volts (0.02 x 24 = 0.48). This voltage consists of a drop from the connection resistance (0.005 ohms) and a drop from the wire resistance that is unknown.

At the operating current of 4.33 amps, the connection voltage drop is 0.022 volts (4.33 x 0.005 = 0.022). If we subtract this drop from the maximum allowable drop, we get 0.458 volts (0.48 - 0.022 = 0.458) that can result from just the conductor resistance.

We have an equation for voltage drop (V_d) and total resistance (R_t) that is $V_d = R_t$ x 4.33 amps. We can solve for R_t ($R_t = V_d$ ÷ 4.33). The result is 0.106 ohms (R_t equals 0.458 ÷ 4.33 = 0.106) for the 400 foot (122 m) run.

We need to find the resistance in ohms per 1,000 feet of cable (R1000) so that we can look up the conductor size in a table. To solve for ohms per 1,000 feet (R1000), we use the following equation. R_t = R1000 x 400 ÷ 1,000. R1000 = R_t x 2.5. In this case, R1000 equals 0.265 ohms (0.106 x 2.5 = 0.265). From Table 8, Chapter 9 of the *NEC,* or *Code Corner* in *HP80,* we see that #3 (27 mm^2) copper wire has a resistance of 0.245 ohms per 1,000 feet (305 m), so it will meet our requirements.

Typical Copper Conductor Prices

	Range in US$ per foot	
Size (AWG)	*Low*	*High*
10	0.22	0.35
8	0.26	0.42
6	0.30	0.55
4	0.32	0.80
2	0.45	1.25

Does it cost more than #10? Yes. Is it necessary? Yes, if you want to pump water. Will a smaller size work? Yes, but pumping performance will suffer.

The table shows some typical prices for copper conductors in these sizes. Prices vary significantly depending on where and when you buy. No one source (PV equipment distributor, electrical supply, home building store, or hardware store) consistently has the lower prices, so it pays to shop around.

Want to use aluminum conductors with the hope of saving some money over copper? No problem. Since aluminum has a higher resistance than copper, a #1 (42 mm^2) conductor will be needed (resistance is 0.253 ohms per 1,000 feet or 305 m). Special splicing devices rated to connect copper to aluminum will be needed at each end to convert the aluminum conductors back to the copper conductors. Copper is required by the PV modules, many pumps, and some switchgear.

Grounding and Balance of Systems

Although this *Code Corner* primarily deals with module conductors, a few comments on the rest of the system are in order. The module location will require a ground rod to which module frames must be attached. The negative circuit conductor may also be attached to this ground rod, and if this is done, an equipment-grounding conductor must not be used between the modules and the pump. This grounding and bonding system is described in *HP74, Code Corner, Grounding the South Forty.* The Southwest Technology Development Institute (SWTDI) Web site has all of the past *Code Corner* columns in PDF format.

The negative conductor and the equipment-grounding conductors from the pump motor housing and the disconnect switch enclosure will be connected to a second ground rod at the pump.

Since there is no energy storage in the system, and there is only one string of two modules, there is no requirement for overcurrent protection in the circuit (see *NEC* Section 690-9(a) Exception). Only a disconnect switch (listed for DC and rated for load-break operation) will be required at the pump location.

Summary

It takes longer to describe these calculations than to do them. SWTDI is working on an interactive CD-ROM to do some of these calculations for PV systems, and an initial version may be available late in 2001. However, the calculations are relatively straightforward. All that is really required is a copy of the *NEC,* a calculator, and a little time to size conductors properly. In the next *Code Corner,* we will take on a more complicated system.

If you have questions about the *NEC* or the implementation of PV systems following the requirements of the *NEC,* feel free to call, fax, email, or write me. Sandia National Laboratories sponsors my activities in this area as a support function to the PV Industry. This work was supported by the United States Department of Energy under Contract DE-FC04-00AL66794. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

Access

John C. Wiles • Southwest Technology Development Institute (SWTDI), New Mexico State University,
Box 30,001/ MSC 3 SOLAR, Las Cruces, NM 88003
505-646-6105 • Fax: 505-646-3841 • jwiles@nmsu.edu
www.nmsu.edu/~tdi

Sponsor: Sandia National Laboratories, Ward Bower, Department 6218, PO Box 5800 MS 0753,
Albuquerque, NM 87185-0753 • 505-844-5206
Fax: 505-844-6541 • wibower@sandia.gov
www.sandia.gov/pv

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